Sensory Systems

Introduction

Sensation is information that comes from the periphery and is sent to the brain for processing. As in the lesson on motor systems, the sensation we care about in this lesson is that which is perceived by the person. There are so many other sensory fiber tracts (from somewhere in the periphery to somewhere in the brain), but we won't mention those here. We want you laser-focused on the tracts that are processed by the primary somatosensory center, those that come from the body (somato-) and are carried on axons up to the brain.

There are two distinct somatosensory tracts: the DCMLS and the STT. We will define the acronyms within this lesson, but this next part loses its impact if you see their names written out. The STT carries special sensations—temperature and pain—and the DCMLS carries general sensations—touch and position.

This lesson is an overview of the cortical processing of information, the tracts, and the assessment for lesions of those tracts.

Primary Somatosensory Cortex

The parietal lobe is the **sensory lobe**. We are going to focus on the primary somatosensory cortex as if it were the only sensory processing center. Integration of the sensations that we will teach you in this lesson—what the primary somatosensory cortex does—is what much of the parietal lobe does. But it also facilitates integration with vision (the parietal lobe is continuous with the occipital lobe, unlike the frontal lobe which is separated by the central sulcus), audition, and balance. It also handles spatial orientation and word choice for speech.

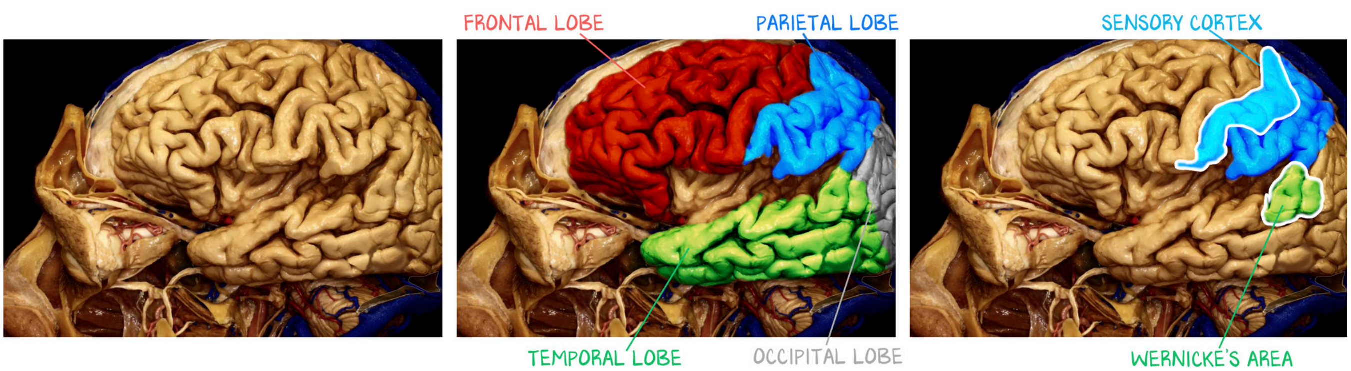

Figure 2.1: Primary Somatosensory Cortex and Parietal Lobe
The first panel is for orientation. We are looking at the lateral aspect of the left hemisphere, with the temporal lobe retracted, the front of the brain on the left, and the occiput on the right. Each panel then identifies specific regions—frontal lobe, parietal lobe, temporal lobe, and occipital lobe—or draws attention to spatial similarities—Wernicke's area is involved in the comprehension of speech. When the Sylvian fissure is not retracted, Wernicke's area will come close to both the sensory and motor cortices. Loss of this area compromises intelligibility—the words come out with rhythm and ease; they just aren't comprehensible.

The **primary somatosensory cortex** is located in the **parietal lobe**, just posterior to the central sulcus. The **central sulcus** separates the anterior frontal lobe and motor cortex from the posterior parietal lobe and sensory cortex. The primary somatosensory cortex begins medially, within the Sylvian fissure, and in line with the primary motor cortex. The **cell bodies** of the primary somatosensory cortex neurons are found in the superficial grey matter that lines the contours of the gyri. The cell bodies of these neurons have axons coming to them from the thalamus, the sensory relay center. This is on the lateral side of the brain, right smack in the middle along its length, and so it is irrigated primarily by the **middle cerebral artery**. It does wrap around to the medial portion of the cortex, and so the most medial portion is irrigated by the **anterior cerebral artery**, just like you saw in *Motor Systems*.

The sensory homunculus represents the different degrees to which the skin of a given body part is innervated by the primary somatosensory cortex. It maps closely (but not perfectly) to the motor homunculus. This makes sense because more sensory inputs are required to plan complex and fine motor movements. The larger the area occupied by a structure, the more neurons are dedicated to it. **More neurons mean finer motor control.** Specifically, the largest numbers of neurons are committed to the face (mainly the tongue, lips, and jaw) and hands—the muscles that perform the most difficult and coordinated movements. You did read that correctly. More sensory neurons dedicated to a structure enables greater fine motor control. **More neurons also means more sensitive and precise sensation.** For example, two-point discrimination (being able to tell there are two points of contact rather than perceiving one) on the back is approximately 40 mm, whereas it is as low as 2 mm on the fingertips.

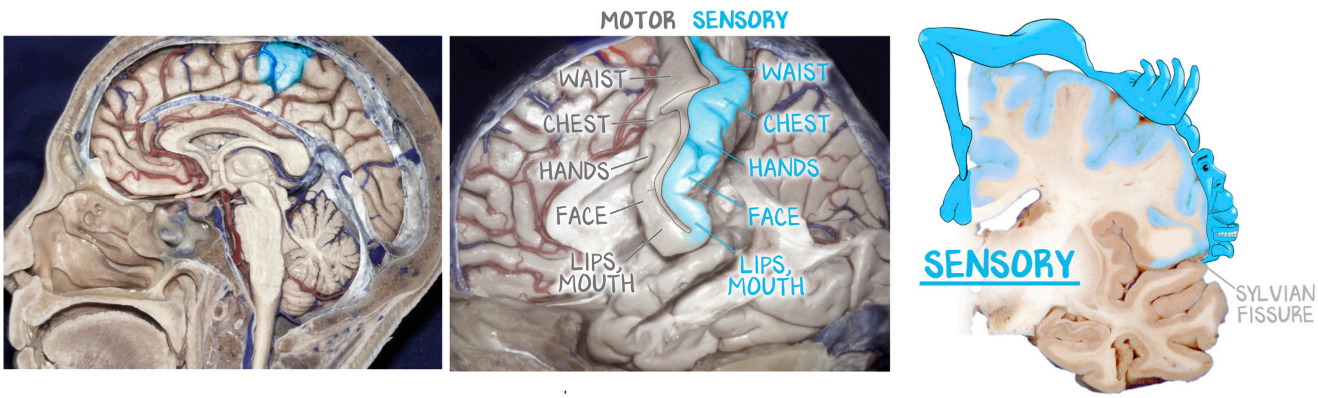

Figure 2.2: Primary Motor Cortex: Homunculus
The primary somatosensory cortex has a topographic representation of the body. The more superior the muscle in the body, the more lateral its representation in the primary somatosensory cortex (more or less). The more inferior the muscle in the body, the more medial its representation in the primary somatosensory cortex. The more surface area dedicated to a muscle group, the larger its representation in the homunculus—the tongue, face, and hands have the most neurons dedicated to them. The illustration on the left demonstrates a mid-sagittal view, showing that the primary somatosensory cortex is the medial portion of the precentral gyrus, does not involve the cingulate gyrus, and wraps around to the lateral surface. The second illustration shows the same mid-sagittal view, but with the primary somatosensory cortex (in blue), primary motor cortex (not highlighted), and temporal lobe left in place to maintain the natural anatomy.

The homunculus has implications for stroke. The middle cerebral artery perfuses the area that is responsible for the face, hands, and trunk, the MCA territory. The anterior cerebral artery perfuses the area that innervates the genitals, feet, and part of the legs, the ACA territory. An infarct in either territory will present with the focal loss of sensation in the organs the territories are responsible for. Between the two circulations is a watershed area. A hypotensive event could impact the most distal areas of the two and is the most nebulous to define, but there must be a transition from ACA to MCA, somewhere between the knee and shoulder.

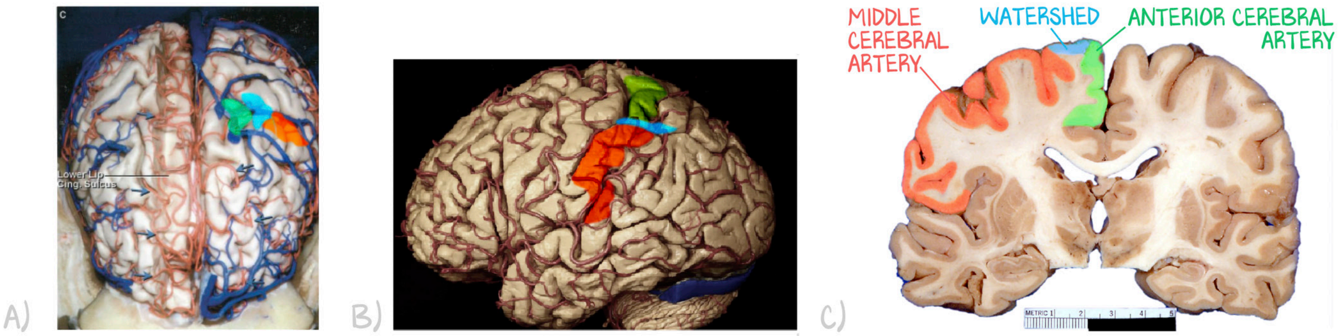

Figure 2.3: Blood supply of the Somatosensory Cortex
(a) Superior view of the brain. On the left side of the image, the medial frontal lobe has been removed to show the arteries penetrating the sulci. The right side of the image (left side of the patient) shows the relative contributions of the anterior cerebral artery and middle cerebral artery from this perspective. (b) This panel demonstrates how the middle cerebral artery is responsible for the majority of the primary somatosensory cortex, as well as the watershed from a lateral view. (c) This panel demonstrates the anterior and middle cerebral arteries' territory of the somatosensory cortex (representational, not exactly anatomic) and the watershed area between them. This caption should sound VERY familiar—it is Figure 1.3's. Somatosensory replaced motor in this figure copy.

Pathway 1: DCMLS

Sensory neuron axons travel on the ipsilateral side of the spinal cord then decussate (switch sides) within the pyramids in the medulla and continue up the brainstem on the contralateral side of their origin. The **sensory tracts** of the DCMLS **bring the perception of sensation to the contralateral brain**. We're going for a deep dive, so ensure to use the figure along with the text.

The dorsal column-medial lemniscus system (DCMLS) carries general sensation. General sensations include **proprioception** (understanding the body's spatial location and speed of movement), **vibration**, **touch**, **pressure**, and tickle senses. The tract is named for where the axons of the neurons of the tract exist in the spinal cord and brainstem. The DCMLS doesn't run in the dorsal columns; its myelinated axons—its fascicles—*are* the dorsal columns of the spinal cord. The DCMLS doesn't run through the medial lemniscus; its fascicles *are* the medial lemniscus of the brainstem. The sensation goes from the periphery towards the brain, so we begin at the periphery.

The cell body of a peripheral **sensory neuron** is located in the **dorsal root ganglion** outside of the spinal cord. Peripheral nervous ganglia are made from **neural crest** cells. They have an axon that immediately bifurcates as it leaves the ganglion. Sensory neurons have one projection to the **skin** and another projection up the spinal cord towards the medulla. As implied by the name of the system that these neurons are in, the axons of this tract make up the **dorsal columns** of the spinal cord. The dorsal columns are topographically arranged. Axons enter the spinal cord from the posterior horn. The posterior horn is lateral to the dorsal columns. The first axon to enter the dorsal columns will enter from the lateral side. Because newer fibers will enter laterally, the first neuron takes up residence in the medial dorsal columns. That means the **most medial axons** are the **most distal** (sacral) **axons**. As axons are added up the spinal cord, they are added sequentially—sacral, lumbar, thoracic, then cervical at the most lateral position in the midbrain (cervical axons are not present below the cervical region of the spinal cord). The nerve has been traveling on the **ipsilateral side** as the sensation. As it reaches the medulla, it synapses with its second-order neuron in the pathway.

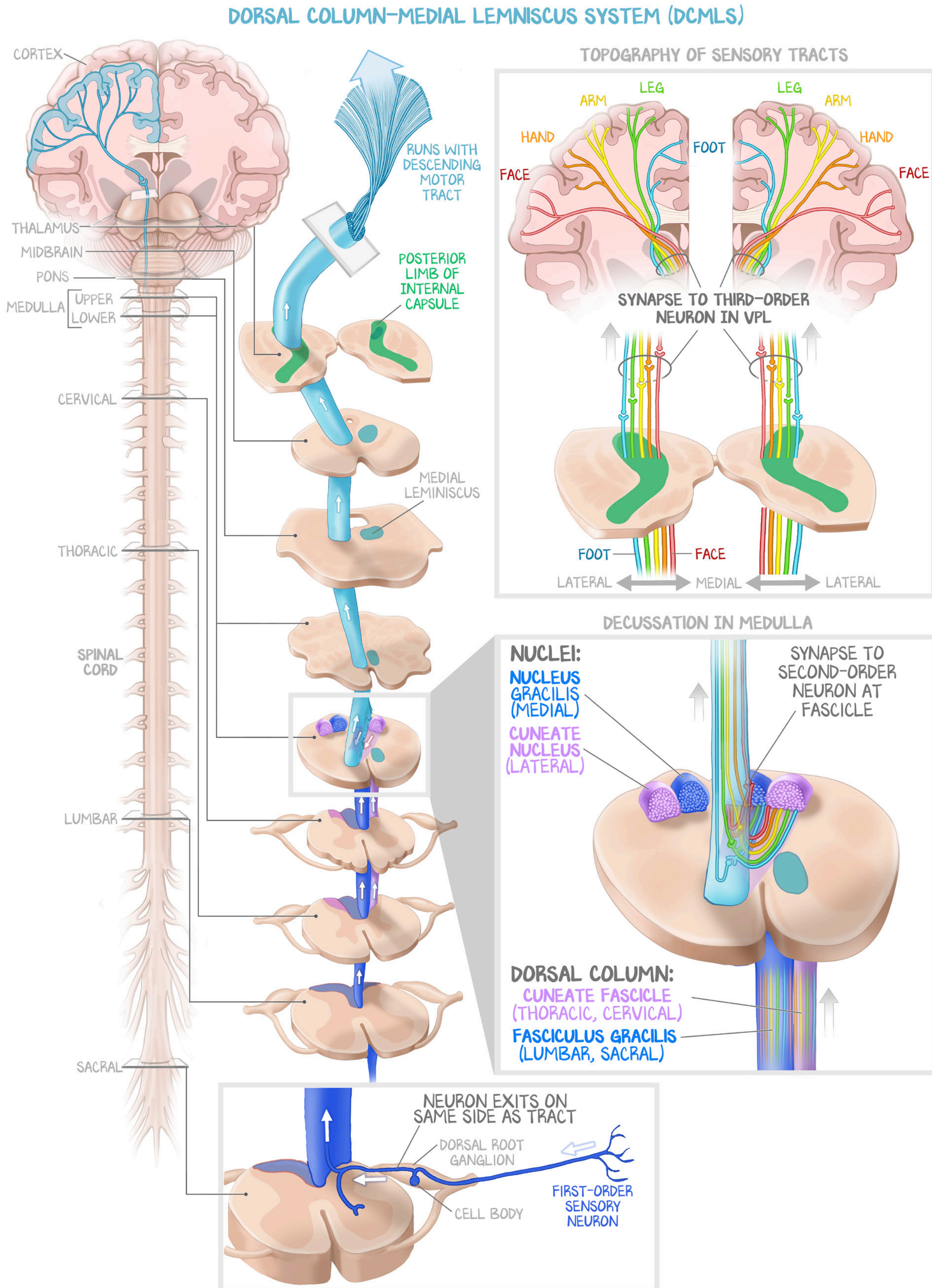

Figure 2.4: Sensory Pathways—DCMLS

A nerve fascicle is a bundle of axons. In the central nervous system, only like-minded axons hang out in a given fascicle, and only the cell bodies of like-minded neurons hang out in a given nucleus. The DCMLS is so strict about this policy that it even segregates fascicles and nuclei based on their vertebral level. The **medial fascicle** (unfortunately still called by its Latin name, fasciculus gracilis) will synapse on the **medial nucleus** (aka nucleus gracilis) in the distal medulla. The medial axons, those that were added first, travel the most medially. The medial fascicle carries the axons of sacral and lumbar cell bodies. The **lateral fascicle** (cuneate fascicle) synapses with the **lateral nucleus** (cuneate nucleus) in the distal medulla, and the lateral-most axons are from the highest vertebral level. The change from Latin to English was intentional. We recommend the discontinuation of the use of "gracilis" and "cuneatus" altogether, but since not enough people agree, we'll turn it into a mnemonic. "Latin first, English later" can help you remember which one is which, the medial being "older" (longer) in the directionality of the tract, like the Latin language is older than English.

The second-order sensory neuron then **crosses the midline** (decussates) within the medullary pyramids, which means that **cortical perception** of the stimulus is perceived on the **contralateral side**. The sensory neurons that cross were named the **internal arcuate fibers**. Like the "pyramids of the motor cortex," the **medial lemniscus** is simply the location of the axons of these second-order neurons. The crossing is topographic. The axons were piled into the brainstem medial (distal) to lateral (proximal), and the axons terminate on neurons. Because the crossing is topographic and is known to be distal first, the synapsing on neurons, ensuring that the axons that cross are discontinuous with the axons in the fascicle, enables the medial axons to cross first. This is less easily stomached than the corticospinal tracts. (It seems logically improbable, and we expected the lateral/superior crossing to come first, exiting as they entered. But topographic mapping and disease states show us this is the way it works.) This means that the sensation of the foot of the DCMLS crosses with the foot of the corticospinal tract. **The directionality is NOT what matters.** Whether it "crosses first" or "crosses last" is irrelevant—the sensation for the face and the motor for the face cross at the same time.

Unlike the "medullary pyramids of motor axons," the medial lemniscus keeps its name as it ascends the medial anterior of the brainstem through the medulla, pons, and midbrain. As it reaches the deep brain, the second-order neuron synapses on a **third-order neuron** in the ventral posterolateral nucleus (which we will refer to only as VPL) of the **thalamus**.

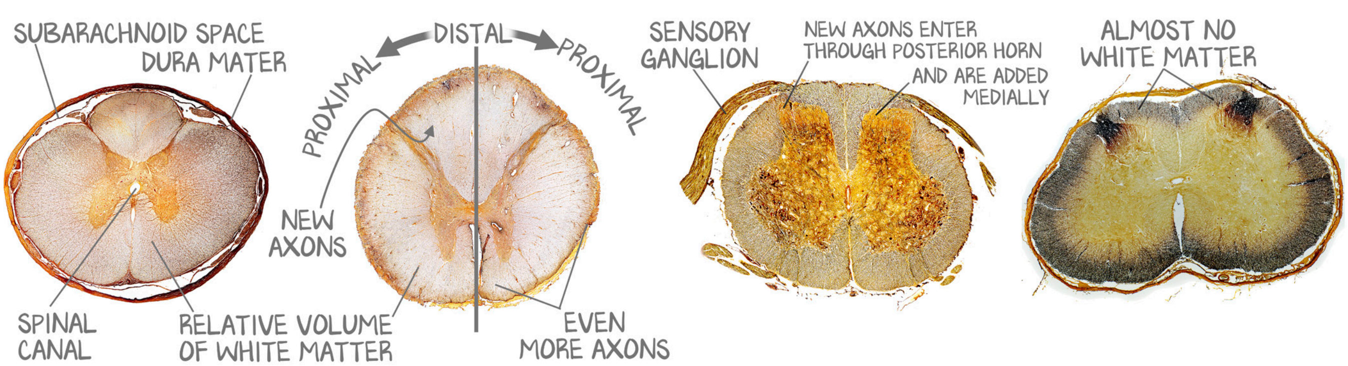

Figure 2.5: DCMLS in Slices
Cervical vertebra (left) showing abundant axons in all tracts. The anatomic separation of the cuneate and gracilis fascicles is subtle and may have been made more visible during the processing of the specimen. We added a visual aid on the right side. The thoracic spinal cord (center left) demonstrates the topography of the left and right DCMLS—the fibers are added sequentially on both sides, so the most distal axons are inserted medially. The lumbar cord sample (center right) shows where the fibers are coming from and where they go. The sacral cord (right) is shown to emphasize how the white matter reduces in size, and grey matter becomes proportionately larger. We'll show you the cauda equina later in this course; the peripheral nerves were removed from this sample to enable you to focus on the sensory tracts.

That third-order neuron has an axonal projection through the **posterior limb** of the **internal capsule**, the same path the descending motor tract took, with the same topography—superior/medial, inferior/lateral—to finally arrive to synapse on a sensory neuron in the primary somatosensory cortex. And, like the corticospinal tract, the topography is arranged to keep the superior structures (face, hands) more medial and the inferior structures (toes, legs) more lateral. This is why a stroke of the internal capsule is so devastating. It can compromise all motor function and sensation (including the STT fibers, discussed below).

Pathway 2: STT

The spinothalamic tract (STT) shares many similarities with the DCMLS. There are three major differences: where it exists in the spinal cord, the topographic arrangement, and where the synapse-and-decussation occurs.

First: synapse and decussation. The first-order neuron is in the dorsal root ganglion and receives an impulse from the skin. The action potential travels along the bifurcated axon—same as in the DCMLS. As it enters the posterior horn of the spinal cord, it **immediately synapses** with its second-order neuron, which immediately **decussates at that level**. Both sensory systems synapse and decussate immediately, though the STT does it only at the vertebral level associated with its sensory neuron. Because synapse and decussation occur at the vertebral level bilaterally, both axons cross the midline anterior to the spinal canal and can be compromised by defects in the spinal canal.

Second: location in the spinal cord. The STT is found in the **lateral aspect** of the **anterior** spinal cord. It runs in that location until synapsing on a third-order neuron in the VPL of the thalamus. The entire STT tract, except for the neuron in the peripheral nerve outside the spinal cord, is **contralateral** to the affected side.

Third: topography. The axons of the most distal neurons are added to the most lateral position, with new fibers being added medially. Thus, the topography is reversed from that of the DCMLS. The cervical fibers are the most medial and the sacral fibers the most lateral. The STT runs as one fascicle. The axons synapse on the VPL of the thalamus before ascending to the cortex and primary somatosensory center.

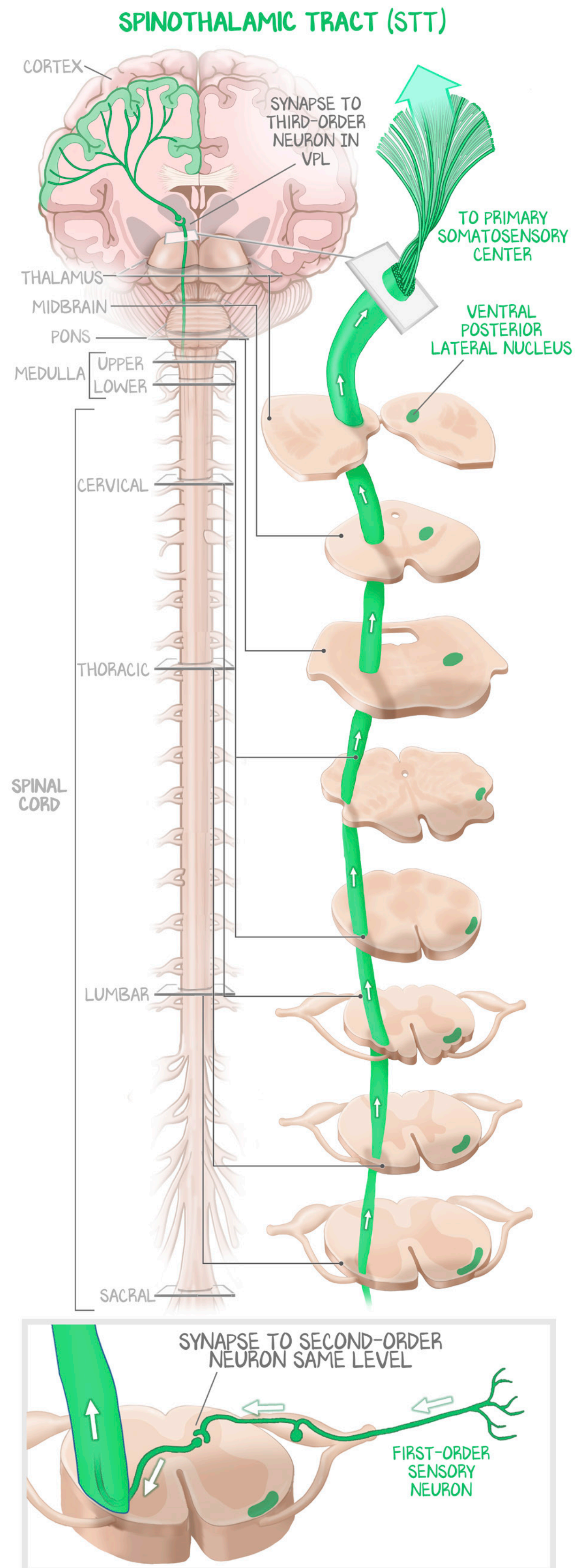

Figure 2.6: Spinothalamic Tract

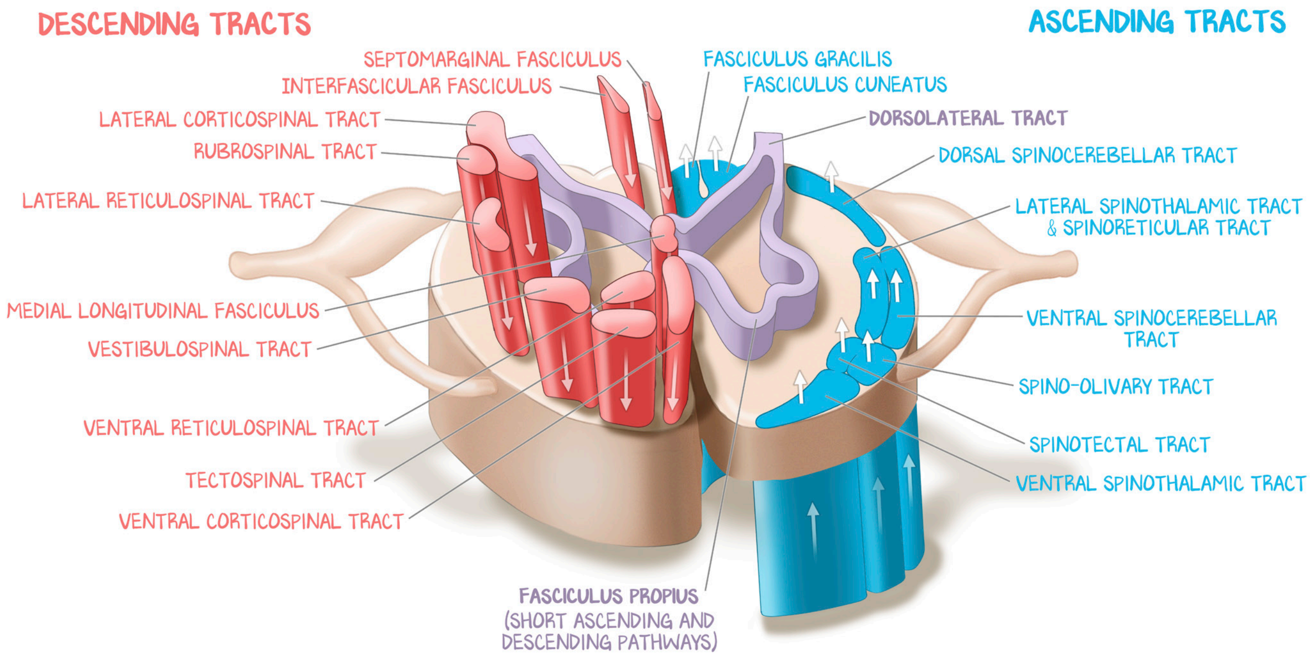

Figure 2.7: All the Tracts
We want to show you that there is so much more to the spinal cord. For example, the tract of Lissauer allows for incoming sensory fibers of the lateral spinothalamic tract and the anterior spinothalamic tract to ascend prior to synapsing, breaking the rule that the tracts synapse and decussate at the level they enter. We haven't mentioned an anterior spinothalamic tract. And look at how many there are! There are many unperceived sensory tracts that rise into areas that are not the VLP of the thalamus and don't go to the cortex. We have omitted them from our discussion because what you are going to do with every patient with a neurologic deficit is assess motor (CST) and sensation (DCMLS and STT). Then, when you stand someone up to see if they can walk, you assess the cerebellum. If you become a neurologist, you may become savvier and anticipate diagnoses before the MRI comes back and confirms your suspicion. For most, the three tracts are all you need. And don't worry, we'll introduce some of these tracts in the coming lessons.

Assessing Sensation

A key finding to facilitate your localization of a lesion of the CNS: **STT lesions always present with contralateral loss of pain and temperature except at the site of the lesion**. No matter how high up, symptoms are always contralateral, and everything below the lesion will demonstrate loss of sensation (anesthesia) or a decrease in sensation (paresthesia) of temperature and pain.

Anesthesia is quite literally the loss of all bodily sensation, and hemianesthesia is the loss of sensation in half the body. As you have just learned, there are two important sensory tracts—general sensation and pain/temp—that run to the cortex. Later in the module, we will discuss the pain and analgesic tracts of the brainstem and the use of anesthesia to block pain signals. Because we don't want you to conflate the anesthesizing of pain fibers and the loss of sensation of one half of the body (hemianesthesia), we are going to use the term "hemisensory loss" instead. When a sensory tract is not defined, we mean both pain/temperature and general sensation. When we mean only one tract, it will proceed hemisensory loss, such as "DCMLS hemisensory loss."

Because the DCMLS is ipsilateral in the spinal cord but contralateral in the brainstem and brain, any lesion of the spinal cord that affects both the DCMLS and STT will have ipsilateral general touch sensation loss and contralateral pain and temperature sensation loss. When the sensory defects are **incongruent, the lesion is in the cord**. You should be able to pair this with ipsilateral motor findings because both the DCMLS and the lateral corticospinal tract cross in the medulla.

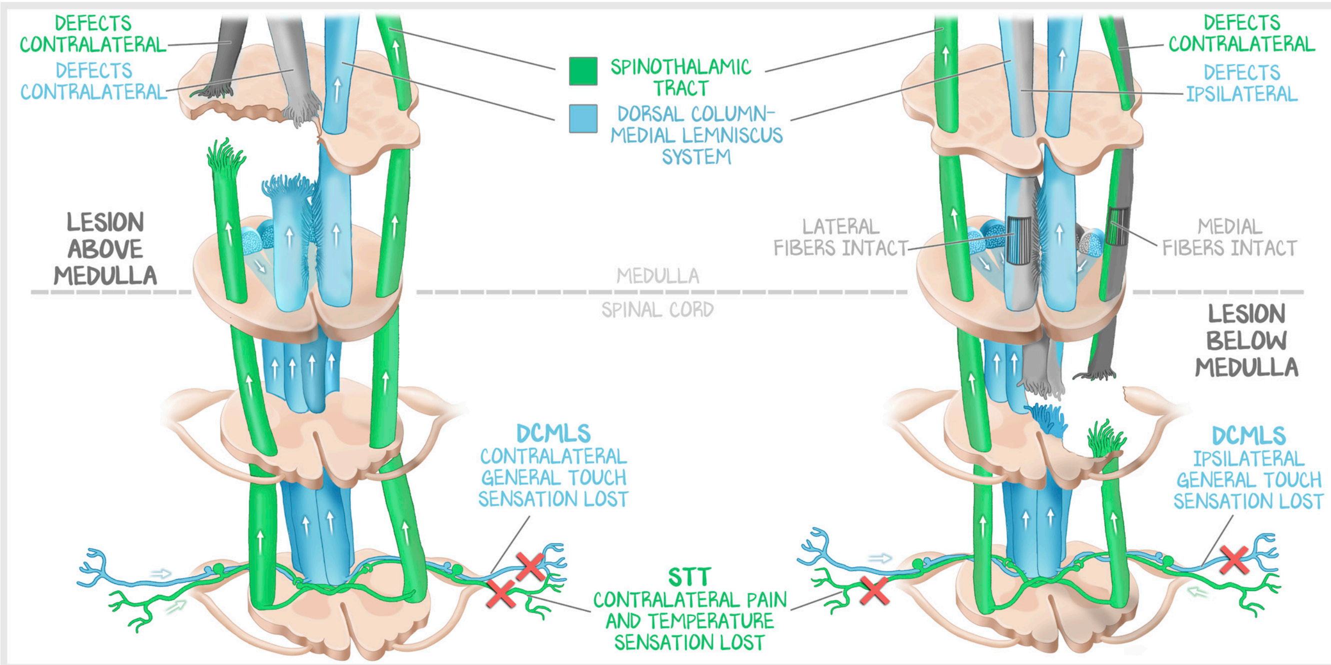

Figure 2.8: Assessing Sensory Tracts
Because neurons of all three tracts eventually cross sides—the STT at the vertebral level that the first synapse occurred (synapse and cross) and the corticospinal tract and DCMLS at the medullary pyramids—a lesion above the medulla will cause symptoms on the contralateral side to the lesion. Because neurons of the STT cross at the vertebral level of their synapse, whereas the corticospinal tract and DCMLS do not, a lesion will cause ipsilateral defects of the corticospinal tract and DCMLS, but contralateral STT dysfunction.

Skin Sensory Receptors

There are several different types of receptors. If you stimulate the skin, a lot of receptors are activated at the same time. Scandinavian researchers recorded the extracellular potential in peripheral cells. While stimulating the axons, they asked the subjects if they felt anything so that they were able to classify fast- or slow-adapting receptors. Stimulating a single axon did not feel like a normal sensation because any normal sensation involves multiple receptors.

Sensations carried by the DCMLS are activated by **mechanoreceptors**. Each one works a little differently and is located in a layer of skin to match what it senses—touch, vibration, or pressure.

Tactile (Meissner's) corpuscles are located in the dermal papilla and sense fine touch and vibration. They are very sensitive receptors but adapt quickly. They are best used for assessing change. **Merkel's discs** are located at the epidermal-dermal junction and sense touch. These receptors can communicate the duration of a stimulus but also accommodate—they fire fast and frequently when a stimulus changes, but then reach a steady state. **Lamellated (Pacinian) corpuscles** are in the deep dermis and subcutaneous fat and assess for deep pressure and high-frequency vibration. These, like tactile corpuscles, rapidly adapt and discontinue their firing soon after the pressure or vibration is felt. **Bulbous (Ruffini's) corpuscles** are located in the dermis and joint capsules and sense pressure. **Hair follicle receptors** sense the movement of hair.

How do these receptors combine to generate proprioception, two-point discrimination, and coordination? They just do. Stimulating a receptor or even a receptor type without stimulating the others (which is only possible in experimental settings) would produce a completely foreign sensation. Anything a human brain perceives is a combination of all of them working in concert.

Sensation carried by the STT is activated by **nociceptors**. Each responds to a specific noxious agent. There are chemical, thermal, and mechanical nociceptors. Banging your hand on the table feels different than grabbing a pot handle you didn't anticipate was hot. They both hurt, but they hurt differently. As is classically asked in response to a patient's presentation of chest pain, "*is it stabbing, burning, or crushing?*" The quality of the pain, its character, can help increase or decrease the pretest possibility of many causes of chest pain. Because these generate pain, they are carried by the STT. But which axons depolarize in STT, and from where that action potential was initiated will ultimately provide a characterization of the pain. The patient reports a symptom, pain. You inquire about the timing, characterization, and localization of that pain.

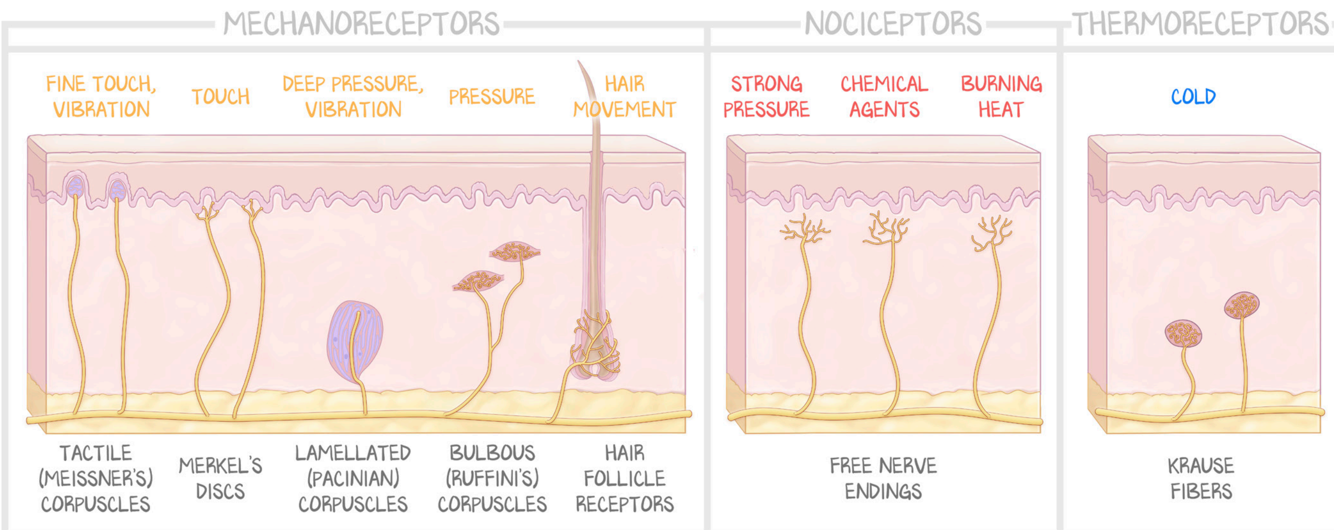

Figure 2.9: Skin Receptors
Sensation—either generalized touch, pain, or temperature—is sensed by receptors in the skin. There are mechanoreceptors (DCMLS receptors transmitted to the spinal cord by DCMLS sensory neurons), nociceptors (STT receptors transmitted to the spinal cord by STT sensory neurons), and thermoreceptors (STT receptors transmitted to the spinal cord by STT sensory neurons). Each receptor has an axon. Together, with multiple signals coming into the cortex all the time, the perception of pain, temperature, and general touch is the result of the sum of all receptors all the time.

Nociceptors are specialized receptors that are all **free nerve endings**. They are present everywhere in the body—in skin, bone, muscle, most internal organs, blood vessels, and the meninges. The sensory neurons are found in the dorsal root ganglion with axonal projections to the spinal cord, just like other sensory neurons. Nociceptors are not present in the CNS. Nociceptors vary in their selectivity. **Mechanical nociceptors**, some of which are quite selective, respond to strong pressure—in particular, pressure from sharp objects. **Chemical nociceptors**, which are mechanically insensitive, respond to a variety of agents, including K^+, extremes of pH, and neuroactive substances such as histamine. **Thermal nociceptors** signal burning heat (above ~45°C/113°F, when tissues begin to be destroyed).

Be cautious: most temperature receptors—**thermoreceptors**, known by the eponym Krause fibers—are actually cold receptors. Use caution around the lookalikes—there are thermal nociceptors that induce the perception of pain, and also the receptors that sense temperature, thermoreceptors. The degree of cold is assessed by Krause corpuscles in the skin, which in turn set a depolarization frequency in their axons (together, "Krause fibers"), depending on how cold it is. A drop in temperature results in more frequent firing. The signal's destination is both to the cortex via the thalamus (you feel the degree of coldness; "warm" is merely how "not cold" it is) and to other brainstem areas that induce heat-seeking behaviors.

Dermatomes

In the Musculoskeletal module, we took on the motor and sensory innervations of the terminal branches of a given plexus and introduced the idea of dermatomes. We left out a discussion of dermatomes in general. Dermatomes are effective methods for figuring out the level of a lesion. By assessing temperature (usually cold metal) and tactile sensation (a gentle stroke of the finger, "*does it feel the same on both sides?*"), a methodical sensory assessment can reveal the diagnosis. You've seen dermatomes before, so we won't belabor the discussion. Put simply, the cutaneous sensation of the skin is cylindrical from the vertebra itself. The dorsal root ganglion on the left side of T5 innervates all of the skin at the level of T5 on the left. Dermatomes **don't cross the midline**. What makes them so hard to comprehend is that humans are not a cylinder. The initial fetus is a fairly tube-like structure, and the neurons are where they are supposed to be on the tube. But then cell divisions proliferate away from the tube, dragging their ectodermal attachments with them. These images below are reproduced from MSK to give you an idea.

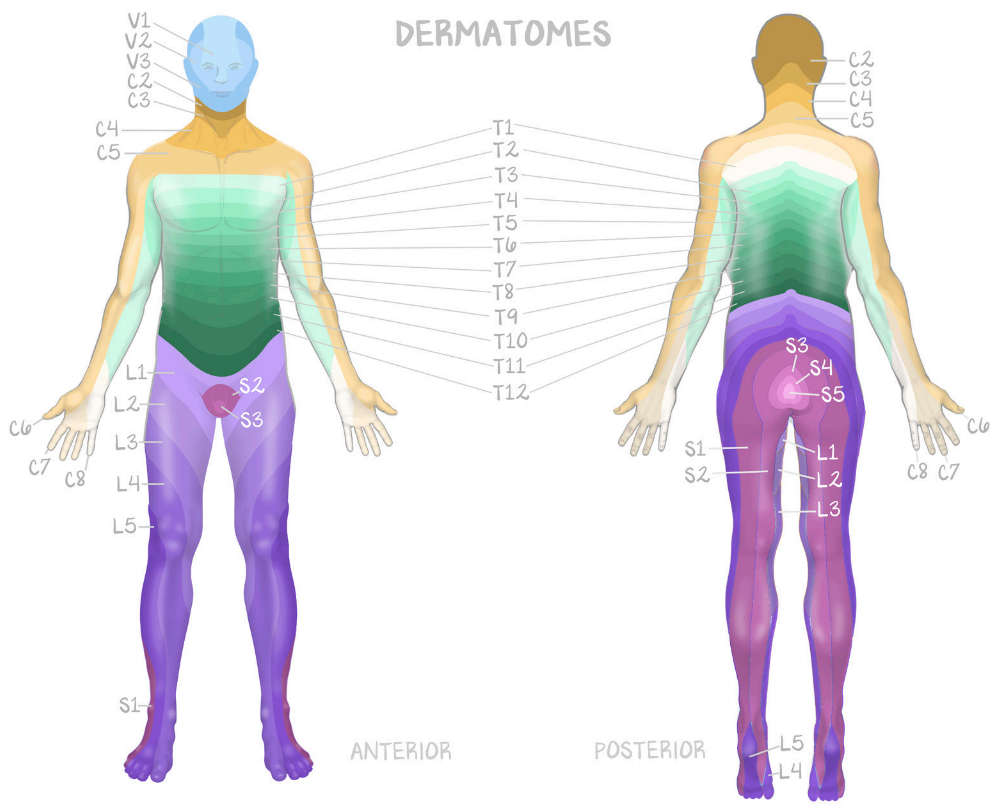

Figure 2.10: Dermatomes
We touched on dermatomes in the MSK module but wanted to provide the dermatome key. It is useful to remind you not only that each dermatome represents the sensation carried by the vertebral nerve at that vertebral level in the spinal cord, but also that peripheral nerves must carry all tracts with them because, like sensation, there are no other means of innervation of those structures without passing within the peripheral nerve.

Citations

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